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Chang, Shoude; Mao, Youxin; Chang, Guangming; Flueraru, Costel

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Jade detection and analysis based on optical coherence tomography images

Shoude Chang

Youxin Mao

National Research Council Canada
Institute for Microstructural Sciences
1200 Montreal Road, M50
Ottawa, Ontario K1A0R6 Canada
E-mail: shoude.chang@nrc.ca

Guangming Chang

Shandong Yingcai University
Jinan, Shandong China

Costel Flueraru

National Research Council Canada
Institute for Microstructural Sciences
1200 Montreal Road, M50
Ottawa, Ontario K1A0R6 Canada

Abstract. Optical coherence tomography is a fundamentally new type of optical sensing technology that can perform high-resolution, cross sectional sensing of the internal structure of materials and biological samples. This work briefly describes its capability of exploring and analyzing the internal structures and textures of various jades. With a depth resolution of 4 μm in jade and penetration range of 5 mm in jade, swept-source OCT could be used as a new powerful instrument to generate 3-D volume data of jade, which is important for applications in jade industry and artwork, particularly for jade detection and classification, counterfeit recognition, and guided artistic carving. © 2010 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3449112]

Subject terms: optical coherence tomography; internal structure analysis; jade estimation; volume data extraction; artwork diagnostics.

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1 Introduction

Optical coherence tomography (OCT) is an emerging technology for high-resolution cross sectional imaging of 3-D structures. The first OCT system was reported by Huang et al. in 1991.¹ Since then, OCT technology has been attracting the attention of researchers all around the world.²⁻⁴

OCT relies on the interferometric measurement of coherent backscattering to probe the structure of test samples such as biological tissues or other turbid materials. It takes advantage of the short temporal coherence of a broadband light source to achieve precise optical sectioning in depth.

Advantages of OCT versus other volume-sensing systems include the following.

1. Higher resolution. This feature enables greater visualization of fine details of the sample. Resolutions for different systems are: OCT, 5 to 10 μm ; ultrasound, 150 μm ; high-resolution computerized tomography (CT), 300 μm ; magnetic resonance imaging (MRI), 1000 μm , respectively.
2. Noninvasive, noncontact. This feature increases safety and ease of use, which is important for applications where the sample is precious and delicate.
3. Fiber optics delivery. As fiber diameter is normally 125 μm , it allows OCT to be used in very small probing spaces, such as tiny holes, slots, and cracks.
4. High speed. The new generation of OCT technology does not need mechanical scanning in depth, which removes the bulky motion parts in an OCT system, and makes the measurement more accurate as well as increases the sensing speed.
5. Potential for additional information from the sample. For example, polarization contrast, Doppler effect, as

well as spectroscopic information could be explored by functional OCT.

6. Use of nonharmful radiation. This feature provides a safe working environment for both testing sample and system user, unlike traditional CT that works with x-rays and ultrasound that relies on mechanical vibration.

In the past decade, OCT systems have been developed mainly for medical and biomedical applications, especially for diagnostics of ophthalmology, dermatology, dentistry, and cardiology.²⁻⁴ To explore the capabilities of OCT systems for probing the internal features of an object, Ref. 5 reported an application for multiple-layer information retrieval and internal biometrics.^{6,7} In addition, because OCT has a voxel resolution of micrometer size, it has potential applications in material investigation⁸ and artwork diagnostics. Reference 9 describes OCT diagnostics used for museum objects, involving stratigraphic applications,¹⁰ varnish layer analysis,^{11,12} structural analysis, and profilometric applications.¹³⁻¹⁶ In Ref. 17, the use of different OCT systems for oil painting layer examination, varnish thickness determination, and environmental influences on paintings on canvas are described.

As an expensive natural stone, jade has a worldwide market. In the jade industry, the main procedures involve detection, assessment, cutting, and artistically carving, basically relying on the human eye and/or experience. Given the advantages listed before, OCT may pave a new avenue to lead the traditional procedure to volume data-based machine vision systems. This work proposes new methods based on statistical analysis of OCT images for detection of jade from raw materials and its quantitative analysis. First experimental proofs of principle are given as well as some perspectives for future applications of our technique are described.

2 Principles of Optical Coherence Tomography

For direct imaging, such as ordinary photography, all the layers reflected from the underneath of an object will be fused together. However, in optical coherence tomography imaging, due to the introduction of a coherence gate generated by an interferometer and broadband light source, the fused layers can be separated from each other.

As is well known, when a partial coherent light source with a Gaussian spectral distribution is used in the interferometer, the detection of light waves from an interferometer can be expressed as:

$$I_d = E_s^2 + E_r^2 + 2E_s E_r \exp(-4 \ln 2 \Delta L^2 / Lc^2) \cos(\Delta L / \lambda_0), \quad (1)$$

where λ_0 is the central wavelength, ΔL is the optical path difference between two arms, and E_s and E_r are electromagnetic waves from the sample and reference arms, respectively. $\exp(-4 \ln 2 \Delta L^2 / Lc^2) \cos(\Delta L / \lambda_0)$ is called coherence function, and Lc is the coherence length, given by

$$Lc = (2 \ln 2 / \pi \pi) (\lambda_0^2 / \Delta \lambda) = 0.44 \lambda_0^2 / \Delta \lambda. \quad (2)$$

In OCT systems, Lc acts as the coherence gate, which directly determines the depth resolution of an OCT system.

Considering that the scanning procedure in time domain (TD)-OCT is actually a procedure of convolution, E_s in Eq. (1) can be expressed by

$$E_s \propto E_r \otimes h_s, \quad (3)$$

where h_s is the impulse response of the sample. Its Fourier transform becomes

$$S_s(\omega) \propto S_r(\omega) \cdot H(\omega). \quad (4)$$

$S_r(\omega)$ and $H(\omega)$ are Fourier transforms of E_r and h_s , respectively. When a 50/50 splitter is used, $S_r(\omega) = 1/2 S_0(\omega)$, where $S_0(\omega)$ is the light source spectrum. Considering the interferometer structure, the signal detected by a sensor is given by

$$I_d(\omega) = |S_r(\omega) + S_r(\omega)H(\omega)|^2 = S(\omega)[1 + H(\omega)]^2, \quad (5)$$

where $S(\omega) = 1/4 S_0^2(\omega)$.

Equation (5) is the foundation of Fourier domain OCT (FD-OCT), the second generation of OCT. Actually, FD-OCT can be further divided by swept-source OCT (SS-OCT) and spectral domain OCT (SD-OCT).^{18,19} SS-OCT and SD-OCT have several advantages over TD-OCT. Due to lack of mechanic motion for depth scans, the FD-OCT system is significantly faster, 50 to 100 times, than TD-OCT. In addition, both FD-OCT and SS-OCT have better sensitivity and signal-to-noise ratio.²⁰ In the experiments described in the following sections, an SS-OCT system has been used to detect and analyze jade samples.

3 Optical Coherence Tomography Technology Applied to Jade Procedures

3.1 Jade Procedures

Jade can be classified into two groups: nephrite or jadeite. Nephrite jade (a silicate of calcium and magnesium) is a kind of Chinese jade existing for more than 5000 years. The features of nephrite are translucency and extreme

toughness (the toughest of any natural stone). Colors of nephrite jade range from pure white to all shades of green. Jadeite jade (silicate of sodium and aluminum) is more rare and expensive. Beside the translucency, it is slightly harder than nephrite jade and often color enhanced. Colors of jadeite range from white to black with intense greens and lavender.

Generally, the procedure of jade has the following steps.

Exploration. This process involves drilling into the mountain side with water-cooled diamond-tipped core drills. The cores are then extracted and examined by eye to determine if the jade will meet the gem grade requirements.

Cutting. After the jade boulders have been broken out, they are then taken to huge diamond saws to be reduced to manageable sizes. The sawyer will also cut windows into the boulder to better expose the texture of the jade inside.

Artistic carving. The jade carver will finally make the raw jade, small or big, into art crafts. During design and carving, the internal pattern, such as marks and textures, may create a lot of risks and opportunities for the artist.

Another interesting nonstandard procedure is the “bet jade.” Sometimes, experienced jade dealers gather at the mining spot to select and purchase the uncut ores. They do so because the price is low, and the expensive jade can be protected if it is there. This procedure is normally called “bet jade.” In Asia, the “bet jade” is a large market, which is not limited to the mining spot.

By means of OCT technologies, the procedure of acquiring could be greatly facilitated. In the exploration and cutting steps, instead of cutting off a large area at the core and a window into the boulder for visual observation, only a small hole could be drilled and a tiny fiber probe inserted into the raw material. Then an OCT system could be used to analyze if the jade is there and what type and quality of the jade will be, which greatly avoids or reduces the waste and damage of the jade. In artistic carving, sometimes the artist has to guess what pattern is hidden underneath the surface of the jade. If the guess is wrong, the planed art work may be destroyed and devalued. However, with the capability of seeing through the jade material to certain depths, OCT could guide the artist to better handle the internal patterns in jade carving.

Another potential application is the discrimination of the fake antique jade wares, which is critical in the antique market. Real ancient jade always carries some ooze and deposit on and under the surface after burial for hundreds or thousands of years. The optical penetration features, for example, the signal intensity decay and texture patterns, are different between the real and fake ones. These features can be detected and described by an OCT system and specially designed algorithms. The first attempt to use OCT to monitor the subsurface morphologies of real and fake archaic jades is due to Yang et al.¹⁵ In this paper, authors are focusing their effort on observing the whitening area of jades. Archaeologically excavated archaic jades normally have

Fig. 1 Swept-source OCT system used in experiments.

different degrees of whitening due to the character of mineral composition, and variations in the underground environments of the jades. However, the artificially whitened jade probably was treated either by burning or by acidification. In Ref. 15, the authors reported that in naturally whitening areas of jade, backscattering intensity is weak, but for fake ones, backscattering intensity is enhanced. In this paper, results were examined by eye and no quantitative analysis was given. Actually, OCT images in this paper show that the jade structure was presented within a couple of hundred microns in depth. So, no meaningful texture could be extracted, especially for the hundreds of microns scale texture structures. It was almost impossible to perform jade texture analysis within such a small depth, because of the limitation of the first generation OCT system they used. Thanks to OCT improvements in recent years, the quality of images has dramatically improved, hence the depth penetration and resolution. In our study we used a homemade fiber-based classical swept-source OCT system. The system, in air, has a probing range and a depth resolution of 8 mm and $7\ \mu\text{m}$, respectively. Thanks to the development of a dedicated statistical analysis of obtained OCT images, we show how to distinguish the jade and nonjade materials, and how we could analyze the internal texture features of different jades. More details of the system configuration and experimental results of OCT imaging for different jades are provided in the next sections.

3.2 Optical Coherence Tomography System used for Jade Characterization

The features of jade can be identified by: hardness, toughness, roughness, translucency, internal patterns and color, as well as refractive index. Roughness and colors can be described by examining surface images of jade. To analyze the roughness by OCT, at least a B-scan, rotary or forward, is needed. Hardness is defined as resistance to scratching, and toughness as resistance to breaking/smashing, which is difficult to measure by optical means. Because there is no reference surface that has a known depth inside a jade body, the measurement of the refractive index is also difficult. However, translucency, surface reflection, and internal patterns could be analyzed by OCT technology.

(a)

(b)

Fig. 2 (a) Unearthed jade used in the experiment. Orange square on animal neck shows the boundary of the background image. Two spots (black and red) indicate the A-scan positions for OCT imaging. (b) Limestone used in the experiment. Blue spot indicates the A-scan position for OCT imaging. (Color online only.)

The OCT setup used in our experiments is illustrated in Fig. 1. The swept source is a commercially available swept laser with a scanning frequency of 20 kHz, a spectral range of 110 nm centered at 1320 nm, and an optical power of 10 mW (Santec, Japan). The light is directed through a 2×2 fiber coupler on the reference mirror and the sample arm. The optical tip is mounted on a galvoscaner, which focuses the light on the sample through a fiber ball lens. The backscattered/reflected signals from both mirror and sample are input into a second 2×2 fiber coupler configured in a Mach-Zehnder geometry. Its two outputs become the input in a balanced detector (New Focus, Santa Clara, California). The output of balanced detection is recorded with a digitizer (Alazartech, Pointe Clare Quebec) at a 100-MHz sampling rate. The signal is resampled to equal frequency intervals and subject to an inverse Fourier transform. The depth resolution of the setup is $7\ \mu\text{m}$, and imaging range for this system is 8 mm in air. Considering the jade has a reflective index about 1.6,²¹ the detection resolution is about $4.4\ \mu\text{m}$, and maximum detecting range is 5 mm in the jade body.

Fig. 3 Three OCT A-scan curves extracted from jade and limestone. Scale 300 corresponds to 2 mm in depth. The black curve was obtained from the jade body. The red curve was obtained from the deposit material on the jade's surface. The blue curve was obtained from the limestone. (Color online only.)

3.3 Jade Detection

To find the optical properties of jade, we first performed a depth scan (A-scan) of OCT on the jade body and nonjade material deposited on its surface. The photograph in Fig. 2(a) shows an unearthed jade (dark greenish) with some deposit (whiteish) material wrapped around it. Two OCT A-scan spots are marked in the photograph. As a comparison, an A-scan was also performed on a common limestone shown in Fig. 2(b).

Figure 3 provides three OCT A-scan curves. The x axis represents the A-scan depth, where scale 300 corresponds to 2 mm. The black curve is the OCT signal obtained from the jade body and the red curve is extracted from the deposit material on the jade surface. The blue curve is obtained from the limestone. There are two obvious differences between the jade signal and nonjade signal: surface reflection and internal distribution. There is about 20-dB difference in signal intensity between jade and nonjade materials. In the top area, 0 to 100 in Fig. 3, the OCT signal of jade has flatter distribution and richer structure than those of nonjade. Hence, a simple distinguishing criterion can be given by such a value:

$$D = |S_{\max} - S_{\text{ref}}| \cdot \text{var}(S_{\text{top}}), \quad (6)$$

where $S_{\max}$ is the maximum value of the OCT signal, which is actually the signal reflected from top surface of the sample. S_{ref} represents the nonsignal reference, which can be defined as the mean OCT signal in the deepest area, for example, the area 250 to 300 in Fig. 3. $|S_{\max} - S_{\text{ref}}|$ gives the relative intensity of surface reflection, which could be used to represent the translucency of the testing material. The smaller the value is, the more translucent/transparent the sample could be. Translucency is the most important feature to distinguish jade from nonjade, particularly for the potential jade boulders. S_{top} is the top area in the OCT signal where the obvious internal structures of jade exist, for example, the area 1 to 100 in Fig. 2. $\text{var}(S_{\text{top}})$ denotes a variance of S_{top} , which describes the flatness of the OCT signal in the defined top area. The smaller the value is, the richer the internal structure it may have. D value can be

	Jade body	Deposit material	Limestone
D value	1.1203×10^3	5.2755×10^3	5.8501×10^3

used to represent the translucency and internal structures of the test sample. A smaller D value reflects a more translucent material that contains richer internal structures.

Given Eq. (6), the D values for the jade body, deposit material, and limestone are listed in Table 1. From those values, the jade can be distinguished by simply setting a threshold.

3.4 Jade Analysis

Although the D value can provide a rough estimation of a jade, more description may still be needed for internal texture analysis, which is important for classification of different types of jade. Texture analysis techniques can be classified into three groups:²² 1. statistical technologies based on region histograms and their moments; 2. spectral technologies based on the autocorrelation function or power spectrum of a region; and 3. structural technologies based on pattern primitives. Algorithms for texture analysis of OCT images were previously reported for biomedical applications. In Ref. 23, authors performed the texture analysis for tissue classification based on the structural and speckle content in OCT images. In Ref. 24, the authors presented an automated algorithm that uses texture analysis to detect bladder cancer from OCT images. Based on the three approaches: statistical, structural, and spectral, 74 texture features are extracted for each image in their training set.

The textures of jades are significantly different from those in biomedical OCT images. They almost have no continuous edges, solid borders, or closed subareas inside. They look more like galaxy patterns. Hence, statistics may be the only tool for texture feature description. In this work, we proposed to extract six parameters from an OCT image.

1. Entropy of OCT image, defined by

$$E_{ir} = - \sum_i [H_{\text{his}}(i)] \cdot \log_2[H_{\text{his}}(i)], \quad (7)$$

where $H_{\text{his}}(i)$ is the histogram of the OCT image, and i represents the individual gray level in the OCT image. The histogram gives the probability distribution of gray levels existing in an OCT image. E_{ir} describes the main shape of the histogram and how rich the gray levels are contained in an OCT texture. The bigger the E_{ir} , the richer the gray levels in the OCT image.

2. Half-peak width of the histogram of the OCT image, defined by

$$W_{\text{hp}} = [H_F - H_L] / \text{max}(\text{gray level}). \quad (8)$$

H_F is the first histogram line number, where the histogram has a value greater than or equal to the half maximum of the histogram. H_L is the last histogram line whose value is greater than or equal to the half maximum of the histogram. $\text{Max}(\text{gray level})$ is the

maximum number of gray levels in the image. In our experiments, all images are finally normalized to 8 bits of gray level, i.e., 256 gray levels. W_{hp} is a normalized value. A small W_{hp} indicates a sharp peak in the histogram and a narrow gray-level range in the OCT texture.

3. Standard deviation of histogram of the OCT image. This parameter estimates the roughness of the histogram of an OCT image.
The prior three parameters are used to statistically describe the probability distribution of gray levels in an OCT image.
4. Average gray value of an OCT image. It estimates how strong and how much texture can exist in the jade sample.
5. Standard deviation of OCT image, and 6. variance of OCT image. Both are used to represent the global roughness of an OCT image.

These latter three parameters are statistical tools directly used in an OCT image, rather than its histogram.

Based on these six parameters, a texture vector can be constructed by

$$\mathbf{V} = a_1 f_1 \mathbf{v}_1 + a_2 f_2 \mathbf{v}_2 + a_3 f_3 \mathbf{v}_3 + a_4 f_4 \mathbf{v}_4 + a_5 f_5 \mathbf{v}_5 + a_6 f_6 \mathbf{v}_6, \quad (9)$$

where, f_1 through f_6 denote entropy, half peak width, Standard deviation of the OCT histogram, average gray value, standard deviation, and variance of OCT, respectively. $\mathbf{v}_1$ through $\mathbf{v}_6$ are the unit vectors representing each parameter. Weighting factors for each parameter are given by a_1 through a_6 . The texture vector gives a numerical description of the texture pattern contained in an OCT image of a jade.

To test the method of texture analysis given by Eq. (9), experiments were carried out. Different types of jades, numbered 1 to 6 shown in Figs. 4(a)–4(f) were then OCT imaged. Different than the *en-face* image, the A-scan OCT image contains an open-air area, which is nonobject and needs to be removed before doing texture analysis. We have designed a two-step algorithm to segment the object area. In the first step, a binary mask was created by finding the maximum points in each vertical line (A-scan line). Figure 5(a) shows the OCT image segmented after the first step. Because the maximum pixel may not be located at the object border, the second step is needed to remove these vertical thorns. Figure 5(b) shows the final segmentation result after step 2. In the segmented OCT image, the pixels in the open-air area are not counted in the jade analysis.

Table 2 provides the values of six parameters of the six jades shown in Fig. 4. For each set of parameters, all values are normalized from 0 to 1, which was done by subtracting the minimum and then dividing by the maximum.

Table 3 gives the variances of each parameter for different jades. a_1 to a_6 are weighting factors whose values are given by the order of the values of variances. For example, the parameter with the maximal variance has a weighting factor of 6, and the one with minimal variance has a factor of 1, simply because we have six vector components. All these weighting factors are listed in the second row of Table 3.

The intensity of the texture vector of jade i is given by

$$|\mathbf{V}_i|^2 = \sum_j (a_j f_{ji})^2, \quad j = 1, 2, \dots, 6, \quad (10)$$

which can be used to numerically distinguish the type of jade. The intensities of texture vector of six jades used in the experiments are given in Table 4 and shown in Fig. 6. From these results, six jades can be classified by different $|\mathbf{V}_i|^2$ values. Looking at Fig. 4, jades 3, 4, and 6 contain dense structures such as textures and layers, so they have the higher $|\mathbf{V}|^2$ values. Jade 2 contains the least gray-level distribution (f_2 in Table 2), i.e., more dark areas or more translucent material in the jade body. Although it has clear texture, its $|\mathbf{V}|^2$ value is the smallest. Jades 1 and 5 have the close $|\mathbf{V}|^2$ values; this can be explained because they both have similar signal density and more random-like textures compared to the other jades. In Fig. 4(f), a layer of yellow texture is located 3 mm under the surface, which provides a clue for the artist when carving the jade. There seems to be no general rule for the quality estimation of different jades so far. The D value given in Sec. 3.3 could be used to evaluate the purity of a jade. However, the purest jade may not be the most expensive one. Some jades with beautiful textures are more attractive. Vector $\mathbf{V}$ gives a 6-D data space for the texture and optical features of the sample, which can be used as the general numerical representation of jade. Actually, by adjusting the values of the weighting factors a_j in Eq. (9), the classification results could be modified according to the requirement. By combining D and $\mathbf{V}$, a practical solution could be reached for the specific application.

4 Summary and Discussion

Optical coherence tomography paves a new avenue for exploring and analyzing the internal structure of an object. The micron-level resolution makes it unique in comparison to other tomographic imaging technologies. OCT technology has potential applications in many fields, including medical, security, environmental, and industrial. In this work, we have briefly described the principle of different OCT systems and shown the possibility of their application in jade exploration and analysis.

Jade is almost translucent in IR light, and it has internal texture associated with different types. The detection of jade can be based on this nature. Experiments show that there is a big difference, around 20 dB, of the reflected/backscattered OCT signals between the jade body and the nonjade wrapping material. Also, almost no structure is detected in the nonjade material due to the weak signal. Based on the jade samples we currently have, we proposed a texture analysis method using their OCT signal. Six parameters were used to numerically describe the texture pattern of the jades. To the best of our knowledge, it is the first time the internal crossing sectional structure and texture of jade materials is extracted and analyzed.

Experimental results show that OCT technology could be a useful tool for jade exploration and analysis by machine vision. For example, by drilling a tiny hole in a potential jade boulder and placing a fiber probe into it, the OCT system can analyze if there is jade inside and what type it could be. It will greatly facilitate traditional jade

Fig. 4 Six jades used in the experiments. OCT image size: 4×2 mm for (a) through (e); and 4×3.5 mm for (f). The small red marks denote the OCT B-scan areas. The red spots on jade indicate the A-scan positions for OCT imaging. (Color online only.)

procedures. In addition, with the help of an OCT system, it could avoid the waste in raw material preparation as well as reduce the risk in artistic carving. Another important application is the anticounterfeiting of the expensive jadeware. Although authors in Ref. 15 described the OCT signal dif-

ference between the real and fake jade in the whitening areas, actually, it is not enough for advanced counterfeit antique jade. The real ancient jade always carries some ooze and deposit on and under the surface, after burial for hundreds or thousands of years. People may need to further

Fig. 5 Segmented OCT images of jade 2. OCT image size: 4×2 mm. (a) Segment result after step 1. Many vertical thorns appear unexpectedly. (b) Segment result after step 2. All vertical thorns have been removed.

Fig. 6 Intensities of texture vector $|V|^2$ calculated from six jades.

Table 2 Normalized values of six parameters.

		Jade 1	Jade 2	Jade 3	Jade 4	Jade 5	Jade 6
f_1	Entropy	0.2941	0.2618	1.0000	0.2471	0.3088	0
f_2	Half peak width	0.6543	0	1.0000	0.6543	0.6162	0.1924
f_3	Std dev histogram	0.5972	0.8665	0	0.6573	0.6198	1.0000
f_4	Average gray image	0.8160	0.6748	0.6288	1.0000	0.6656	0
f_5	Std dev image	0	0.1882	0.5926	0.2750	0.2103	1.0000
f_6	Var of image	0.6024	0.6491	0	0.6298	0.5987	1.0000

Table 3 Variances and weighting factors for each vector components.

	f_1	f_2	f_3	f_4	f_5	f_6
Variance	0.1136	0.1307	0.1183	0.1143	0.1301	0.1042
a_i	2	6	4	3	5	1

Table 4 Intensities of texture vector for six jades.

	Jade 1	Jade 2	Jade 3	Jade 4	Jade 5	Jade 6
$ V ^2$	27.8189	17.6935	52.3397	33.8558	25.6501	43.3324

analyze the feature of these substances to distinguish the real antique jade. In addition, even for expensive nonantique jades, there are many counterfeiters on the market. OCT technology could also be used to recognize the artificial ones by analyzing the optical and structural features. For example, miniature air bubbles exist inside many man-made jades and are normally invisible to the human eye, but could be clearly detected by OCT systems. This is our plan for future work.

References

1. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Pullaifto, and J. G. Fujimoto, "Optical coherence tomography," *Science* **254**, 1178–1181 (1991).
2. A. F. Fercher, W. Drexler, C. K. Hitzenberger, and T. Lasser, "Optical coherence tomography—principles and applications," *Rep. Prog. Phys.* **66**, 239–303 (2003).
3. W. Drexler and J. G. Fujimoto, *Optical Coherence Tomography, Technology and Applications*, Springer-Verlag, Berlin (2008).
4. G. Smolka, *Optical Coherence Tomography: Technology, Markets, and Applications 2008–2012*, BioOptics World, Penn Well Corp., New York (2008).
5. S. Chang, X. Cai, and C. Flueraru, "Image enhancement for multilayer information retrieval using full-field optical coherence tomography," *Appl. Opt.* **45**(23), 5967–5975 (2006).
6. Y. Cheng and K. V. Larin, "Artificial fingerprint recognition by using optical coherence tomography with autocorrelation analysis," *Appl. Opt.* **45**, 9238–9245 (2006).
7. S. Chang, Y. Cheng, K. V. Larin, Y. Mao, S. Sherif, and C. Flueraru, "Optical coherence tomography used for security and fingerprint sensing applications," *IET Image Process.* **2**(1), 48–58 (2008).
8. K. Wiesauer, M. Pircher, E. Götzinger, S. Bauer, R. Engelke, G. Ahrens, G. Grützner, C. K. Hitzenberger, and D. Stifter, "En-face scanning optical coherence tomography with ultra-high resolution for material investigation," *Opt. Express* **13**(3), 1015–1024 (2005).
9. P. Targowski, M. Gora, and M. Wojtkowski, "Optical coherence tomography for artwork diagnostics," *Laser Chem.* **2006**, 35373 (2006).
10. A. Szkulmowska, M. Gora, M. Targowska, B. Rouba, D. Stifter, E. Ereur, and P. Targowski, "The applicability of optical coherence tomography at 1.55 μm to the examination of oil paintings," in *Proc. 6th Int. Cong. on Lasers in the Conservation of Artworks (LACONA VI '05)* (2006).
11. H. Liang, M. Cid, R. Cucu, G. Dobre, A. Podoleanu, J. Pedro, and D. Saunders, "En-face optical coherence tomography—a novel application of non-invasive imaging to art conservation," *Opt. Express* **13**, 6133–6144 (2005).
12. E. R. de la Rie, "The influence of varnishes on the appearance of paintings," *Studies in Conservation* **32**(1), 1–13 (1987).
13. M. Spring, H. Liang, B. Peric, D. Saunders, and A. Podoleanu, "Optical coherence tomography—a tool for high resolution non-invasive 3D-imaging of the subsurface structure of paintings," *ICOM Committee For Conservation News* **4**, 633–640 (2008).
14. P. Targowski, B. Rouba, M. Wojtkowski, and A. Kowalczyk, "The application of optical coherence tomography to nondestructive examination of museum objects," *Studies in Conservation* **49**(2), 107–114 (2004).
15. M. L. Yang, C. W. Lu, I. J. Hsu, and C. C. Yang, "The use of optical coherence tomography for monitoring the subsurface morphologies of archaic jades," *Archaeometry* **46**(2), 171–182 (2004).
16. P. Targowski, M. Gora, T. Bajraszewski, M. Skulmowski, B. Rouba, T. Lekawa-Wyslouch, and L. Tyminska-Widmer, "Optical coherence tomography for tracking canvas deformation," *Laser Chem.* **2006**, 93658 (2006).
17. A. Szkulmowska, M. Gora, M. Targowska, B. Rouba, D. Stifter, E. Breuer, and P. Targowski, *Lasers in the Conservation of Artworks*, Springer Proc. Phys. Book Series, Vol. **116**, Springer-Verlag, Berlin (2007).
18. M. A. Choma, M. V. Sarunic, C. Yang, and J. A. Izatt, "Sensitivity advantage of swept source and Fourier domain optical coherence tomography," *Opt. Express* **11**, 2183–2189 (2003).
19. R. Leitgeb, C. K. Hitzenberger, and A. F. Fercher, "Performance of Fourier domain vs. time domain optical coherence tomography," *Opt. Express* **11**, 889–894 (2003).
20. J. F. de Boer, B. Cense, B. Hyle Park, M. C. Pierce, G. J. Tearney, and B. E. Bouma, "Improved signal-to-noise ratio in spectral-domain compared with time-domain optical coherence tomography," *Opt. Lett.* **28**, 2067–2069 (2003).
21. See <http://nature.berkeley.edu/classes/eps2/wisc/ri.html>.
22. I. Pitas, *Digital Image Processing Algorithms and Applications*, Wiley, New York (2000).
23. K. W. Gossage, T. S. Tkaczyk, J. J. Rodriguez, and J. K. Barton, "Texture analysis of optical coherence tomography images: feasibility for tissue classification," *J. Biomed. Opt.* **8**(3), 570–575 (2003).
24. C. A. Lingley-Papadopoulos, M. H. Loew, M. J. Manyak, and J. M. Zara, "Computer recognition of cancer in the urinary bladder using optical coherence tomography and texture analysis," *J. Biomed. Opt.* **13**(2), 024003 (2008).

Shoude Chang obtained his BS in electronic engineering in 1977, his MS in communications and electronic systems in 1986 from China, and his PhD in physics in 1995 from Laval University, Canada. Most of his activities have been related to digital/optical information processing and pattern recognition. As a senior research officer in the National Research Council of Canada, he is currently working on projects involving optical 2-D/3-D imaging, image processing, and pattern recognition, including optical coherence tomography, medical imaging, biometrics, and information security.

Youxin Mao received her BS degree in physics and her MS degree in electronics science from Nankai University, China, in 1982 and 1985, respectively. She received her PhD in optoelectronics from Lancaster University, United Kingdom, in 1995. She was later a research associate with Lancaster University and an NSERC visiting fellowship with the National Research Council in Canada. As a research scientist, she worked in an exploratory research and development group with JDS Uniphase from 1999 to 2003. She has been working on optical coherence tomography in Nankai University and the University of Toronto since 2003. She is currently a research officer for the National Research Council of Canada. Her research interests include optical coherence tomography, high speed and high power wavelength swept laser, and ultrasmall optical fiber probes.

Guangming Chang received his BA degree in Chinese Literature from Qufu Normal University, China, in 1982. He has been engaged in studying jade culture for more than 20 years, with a thousand-jades collection and many publications. He is a member of the Director's Board of Shandong I Ching Academy, a member of the Sina Antique Jade Research Council, and a member of the Shandong Collectors Association. He is currently the chief editor of *The Journal of Shandong Yingcai University*.

Costel Flueraru received an MS in engineering physics and a PhD in physics from the University of Bucharest (Romania). During his PhD program, he conducted research in the Department of Applied Physics (Applied Optics Group), University of Twente, Netherlands. He was a postdoctoral fellow at the University of Postdam, Germany, and the Max Planck Institute for Interfaces and Colloids, Berlin, Germany, where he investigated nonlinear optical properties of organic materials. He was a visiting fellow at the Steacie Institute for Molecular Science, National Research Council (NRC), Canada, before joining the optics group at the Institute for Microstructural Sciences, NRC, in 2001. He is now with the Institute for Microstructural Sciences, National Research Council of Canada.